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PREPRINT

BOUNDARY CONNECTION BEHAVIOR AND CONNECTION DESIGN FOR RETROFITTED UNREINFORCED MASONRY WALLS SUBJECTED TO BLAST LOADS

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14. ABSTRACT
Over the past decade, extensive experimental and analytical research has been conducted on the behavior and resistance of unreinforced masonry (URM) walls retrofitted with methods for increasing ductility. This includes numerous experiments conducted by the Airbase Technologies Division of the Air Force Research Laboratory (AFRL). These retrofit materials varied from soft elastomeric coatings to very stiff composites and metal sheets. Some retrofit materials were strongly bonded to the masonry wall, which resulted in an integrated system response, while others were not bonded to the masonry and the membrane simply acted as a barrier that prevented secondary fragmentation from entering the occupied space. Previous research programs by AFRL and others have focused on the development of the retrofit materials, with the predominant exploratory measure focusing on the maximum inward transverse displacement. However, little emphasis was placed on the real behavior of the boundaries of these systems and the proper and efficient design of connections. This paper discusses an appropriate analytical methodology for the design of retrofit connections to resist impulse loads due to blast. In addition, typical support conditions for URM walls, and the shear, flexure and friction interaction of blast-impulse-loaded retrofitted URM walls at their support boundaries are discussed. The ideas and conclusions presented herein are based on component-level static testing, full scale explosion arena testing, and high fidelity finite element modeling.

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Boundary Condition Behavior and Connection Design for Retrofitted Unreinforced Masonry Walls Subjected to Blast Loads

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ABSTRACT

Over the past decade, extensive experimental and analytical research has been conducted on the behavior and resistance of unreinforced masonry (URM) walls retrofitted with methods for increasing ductility. This includes numerous experiments conducted by the Airbase Technologies Division of the Air Force Research Laboratory (AFRL). These retrofit materials varied from soft elastomeric coatings to very stiff composites and metal sheets. Some retrofit materials were strongly bonded to the masonry wall, which resulted in an integrated system response, while others were not bonded to the masonry and the membrane simply acted as a barrier that prevented secondary fragmentation from entering the occupied space. Previous research programs by AFRL and others have focused on the development of the retrofit materials, with the predominant exploratory measure focusing on the maximum inward transverse displacement. However, little emphasis was placed on the real behavior of the boundaries of these systems and the proper and efficient design of connections. This paper discusses an appropriate analytical methodology for the design of retrofit connections to resist impulse loads due to blast. In addition, typical support conditions for URM walls, and the shear, flexure and friction interaction of blast-impulse-loaded retrofitted URM walls at their support boundaries are discussed. The ideas and conclusions presented herein are based on component-level static testing, full scale explosion arena testing, and high fidelity finite element modeling.

INTRODUCTION

This study is part of an ongoing series of research focusing on the expeditionary retrofits for enhancing the ductility of unreinforced masonry (URM) walls from becoming secondary fragments. The concepts in this paper are applicable for use by both the military and the private sector. The theories explored in this study are only a part of greater efforts researching ways to increase the survivability of a structure. The loading scenario is idealized in Figure 1. An explosive is placed at some standoff along the perimeter and detonated on the exterior of a structure, creating an impulsive shockwave that loads the exterior facade of the structure. Infill URM walls are assumed to be built within a rigid frame structure for this study. It is important to note that the principles in the paper could be applied to soft frame or semi-rigid frame structures, though the complexity of the problem grows exponentially when increasing the variables of moving boundary conditions.

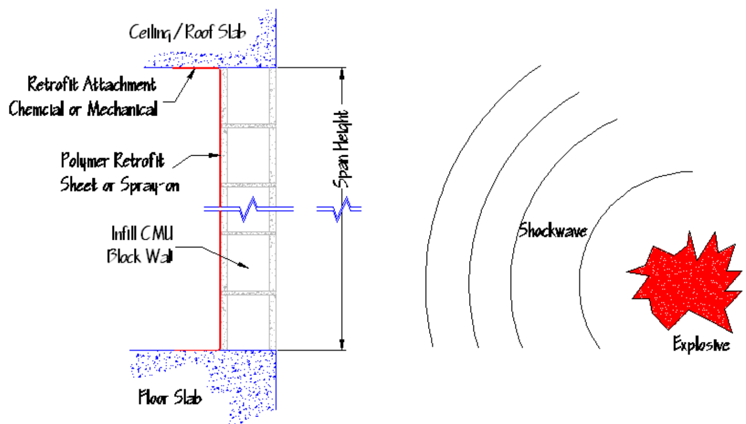


Figure 1 – Profile of Infill Masonry

In Figure 1, the impulsive load would break-up the URM wall sending block fragments into the occupied space of the structure. The retrofit would be installed on the interior side of the URM wall. This paper will focus on the sheet retrofit or catcher system, though the schematic in Figure 1 could be also applicable to bonded retrofits.

BACKGROUND

The initial stages of AFRL's research utilized the spray-on polymer coatings that were not altered for any blast mitigation enhancements (Davidson 2005). As the research progressed, the addition of enhanced materials or designed properties, including both chemical and mechanical properties, intended for blast mitigation were developed. The bonded spray-on systems evolved into trowel-on systems and then into sheet materials for mitigation. Sheet retrofits are not a new concept; materials such as steel, thermal plastics, geotextiles, and wire meshes have been used for blast mitigation purposes. The program discussed herein was developed based on the concept of the sheet retrofit or the membrane catcher system. The objective of this research is to develop methodologies and procedures for designing membrane catcher retrofits with any variable of URM wall design and any membrane material. In this

manner, the retrofit system can be adapted to any boundary condition for existing URM walls. The end goal is to develop mathematical tools for optimizing the designs of URM wall-retrofit systems. Optimization can be in two forms: 1) satisfy a designed threat to insure the protection of the occupants or 2) develop the URM wall-retrofit to take advantage of the full potential energy of the retrofit material.

Several analytical models have been developed to describe the dynamic response of masonry walls with membrane retrofits. All of these models must involve several assumptions: 1) the supporting structure will carry the reaction loads from the masonry wall system and the membrane, 2) strains are uniformly distributed to sheet retrofits and 3) the URM acts in a simply-supported, one-way action. In order to completely understand the URM wall-retrofit interaction, the system must be broken down into components. For this reason, the research program looked at the retrofit membrane and the boundary conditions of the masonry wall separately. Each of these components will be discussed and presented as separate pieces to assist in accounting for the overall capacity of a URM wall-retrofit system. An example of a proposed retrofitting material will also be discussed to demonstrate the analytical model and design procedures.

FLEXURE MODELING

In previous research experiments using sheet or spray-on polymers, the importance of the boundary condition of the masonry wall was ignored. It was thought that unreinforced walls provided only mass, and no resistance, to the wall-retrofit system. Ignoring the absorption capabilities of the masonry inherently changes the dynamic prediction (Fitzmaurice 2006). This study, focused on utilizing the results of existing research on masonry walls that incorporated arching and boundary conditions effects (Jones 1989). The objective was to find a procedure that combines the masonry wall and the sheet retrofit into one resistance function that describes the load versus deflection of a URM wall-retrofit system. The resistance function is a parameter that is commonly used to develop an analytical single-degree-of-freedom response of structural components to blast threats (Biggs 1964). Although the overall URM wall-retrofit system is complex, it can be broken into two simple systems. The first system is the URM wall that can be analyzed separately; the second is the membrane response of the catcher system. Johnson et al. (2010), Fitzmaurice (2006), Moradi et al. (2008), Salim et al. (2007), and Kennedy (2005) showed the membrane response and an alytical comparisons. It was not until recently that the two systems were combined (Johnson et al. 2010).

A Free-Body-Diagram (FBD) of only retrofit membrane is shown in Figure 2; it is assumed that the URM wall-retrofit takes a parabolic shape under a lateral shockwave loading. The lateral loading, p, is the pressure from the detonation being passed to the membrane by the masonry wall. L is the original span length, and T is the resultant force or the internal force in the membrane obtained when the original membrane panel bends to an angle θ at the supports.

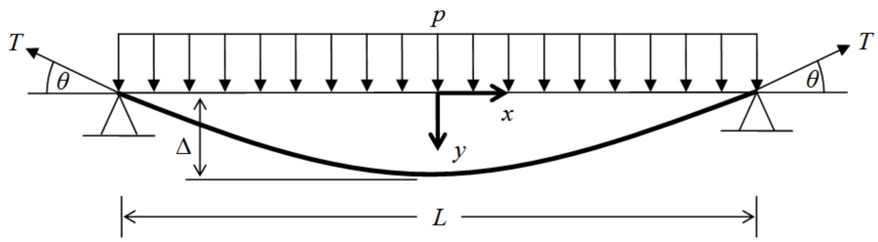


Figure 2 – FBD of Retrofitting Component

The new deformed axial length of the membrane resulting from the applied lateral load is described by the variable L', defined in Equation 1. The full derivation of this equation, along with results of validation experiments, can be found in Johnson et al. (2010) work.

$$L' = \frac{4\Delta}{L}\left[\sqrt{\frac{L^2}{4}+\frac{L^4}{64\Delta^2}}+\left(\frac{L^2}{32\Delta^2}\right)\ln\left(\frac{L}{2}+\sqrt{\frac{L^2}{4}+\frac{L^4}{64\Delta^2}}\right)-\left(\frac{L^2}{32\Delta^2}\right)\ln\left(\frac{L^2}{8\Delta}\right)\right] \qquad \textit{(Eqn. 1)}$$

Simply substituting a value for L and an increment of Δ into Equation 1 results in a calculated L'. The difference of L' and L over L is the axial strain in the sheet:

$$\epsilon = \frac{L'-L}{L} \qquad \textit{(Eqn. 2)}$$

The calculated axial strain can be converted to axial stress, σ, from a stress-verses-strain relationship for a given membrane material. T can be calculated if the given membrane geometric properties are known, i.e..

$$T = \sigma t$$

where t is the thickness of the membrane, and T is units of force/length or a line load along the width of the URM wall opening.

The lateral applied pressure, p, in Figure 2 is related to the membrane axial force by following equation.

$$p = \frac{2\sigma t}{L}\sin\left(\frac{4\Delta}{L}\right) \qquad \textit{(Eqn. 3)}$$

Using the above equations, the static resistance function for a sheet retrofit member can be calculated. Figure 3 provides an example of a static resistance function for an arbitrary condition and material.

Due to the extensive research and documentation of the analytical resistance of masonry, the governing static resistance predictive equations can be found in Jones (1989). For an arching condition, the static resistance function will have an abrupt change in stiffness as illustrated in Figure 4 for an arbitrary example of an arching condition. The next step uses superposition to combine relationships in Figure 3 and Figure 4 to form the static resistance function in Figure 5. The method of combining two resistance functions was first noted in Slawson et al. (2004); which combined the resistance of a URM wall and a geo-fabric used in experimental studies.

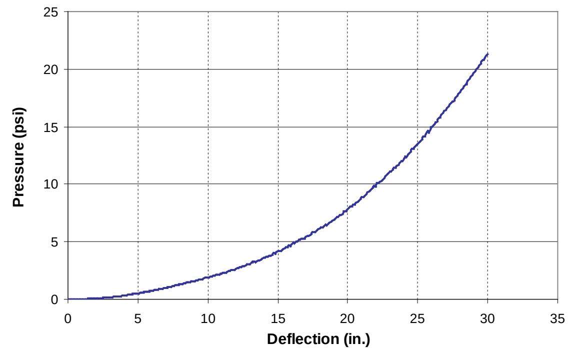


Figure 3 – Arbitrary Static Resistance Function (Membrane Retrofit)

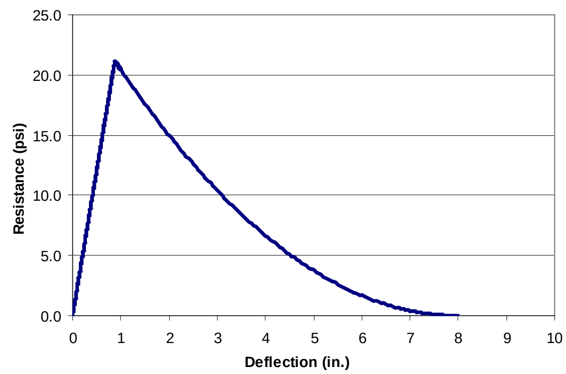


Figure 4 – Arbitrary Static Resistance Function (Arched URM Wall)

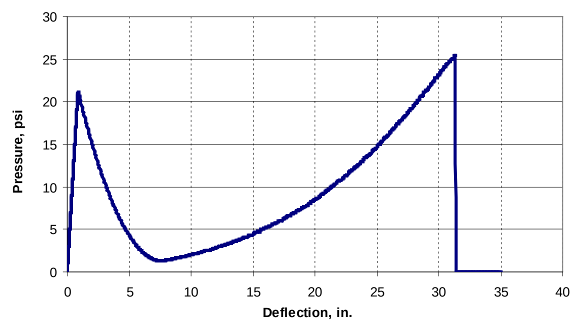


Figure 5 – Arbitrary Static Resistance Function (URM Wall-Retrofit)

In summary, by using the method of superposition the URM wall-retrofit can be broken into manageable pieces for engineering level designs. Again, this is only to develop the analytical resistance of the URM wall-retrofit; the dynamic prediction must still be made using a Single-Degree-of-Freedom (SDOF) analysis (Biggs 1964; Kiger and Salim 1998). From the SDOF analysis, a point of maximum dynamic deflection, Δ_{max}, can be calculated. Working backwards from the Δ_{max}, the designer can then calculate T and apply T to further detailing of the connections.

CONNECTION DETAILING

Research and analyses have shown that stiff retrofit membrane, while advantageous for reducing overall deflections, can become cumbersome and costly to anchor into

structures. Examples of stiff retrofit systems are steel sheets or chain-link fencing. The elastomeric or plastic materials have lower moduli and are able to absorb energy through large plastic deformation, that result in a reduction of the overall developed resultant force (Salim et al. 2007).

With the knowledge and tools now developed to define a resultant axial force in the membrane, *T*, the next step in the procedure is the detailing and design of a workable connection. This procedure identifies three cases; each case represents a mechanism of transferring the calculated forces into the slab or supporting structure. Figure 2 showed the resultant force *T* obtained with respect to the original panel of the membrane at angle θ. In Figure 6, *T* is again used but is now the load applied to the mechanical connector plate.

- Case 1: Forces resulting from the axial force, *T*, are directly transferred into the floor/ceiling slabs. For simplicity the variable *d* in Figure 6 is considered to go to zero and the connection plate is not sufficiently rigid to create a pivot or prying action; no moment arm would exist in the connection plate ($A = T$).
- Case 2: Forces resulting from the axial force, *T*, are multiplied by physical and geometric parameters, moment arm *d*, resulting in prying action on the anchorage. (*A = 2T in this scenario, If the edge distance is not double the plate width, the engineer must recalculate the proper amplification factor*)
- Case 3: Forces resulting from the axial force, *T*, cause yielding or plastic damage to the connecting system. The connection plate bends, which holds *T* at a theoretical constant until the moment arm *d* reduces to zero or until *T* equals the bending resistance of the plate, which starts the prying action again. This concept is thought of as a transition period from Case 2 to Case 1. (*A = 2T to T)*

Although Case 3 provides additional absorption to the URM wall-retrofit, the complexity of the design may lead to an empirical connection solution (Kennedy 2005, Fitzmaurice 2006, and Johnson et al. 2010). In their research, the retrofitting material began to have limiting factors such as slip interaction between the connection plate and supports that was influenced by anchor spacing and bearing at the holes. In all three research efforts, a form of Case 3 occurred with a combination of connection plate bending and direct loading of the membrane retrofit materials to the anchorage. Note that it is recommended that *T* be amplified by a factor of safety when designing the connection to reduce the potential of overloading the anchorage system.

Two materials tested in a URM wall-retrofit study will now be presented. Both materials were chosen for material behaviors with one material having a stiff modulus and the other a lower modulus. Stress-verses-strain relationships for these materials were obtained experimentally and used in URM wall-retrofit design when calculating the static resistance functions for the membrane portion of the wall system. These two materials are believed to cover the outer limits for the spectrum of what a catcher system respons is, and therefore will validate the basis of the analytical models.

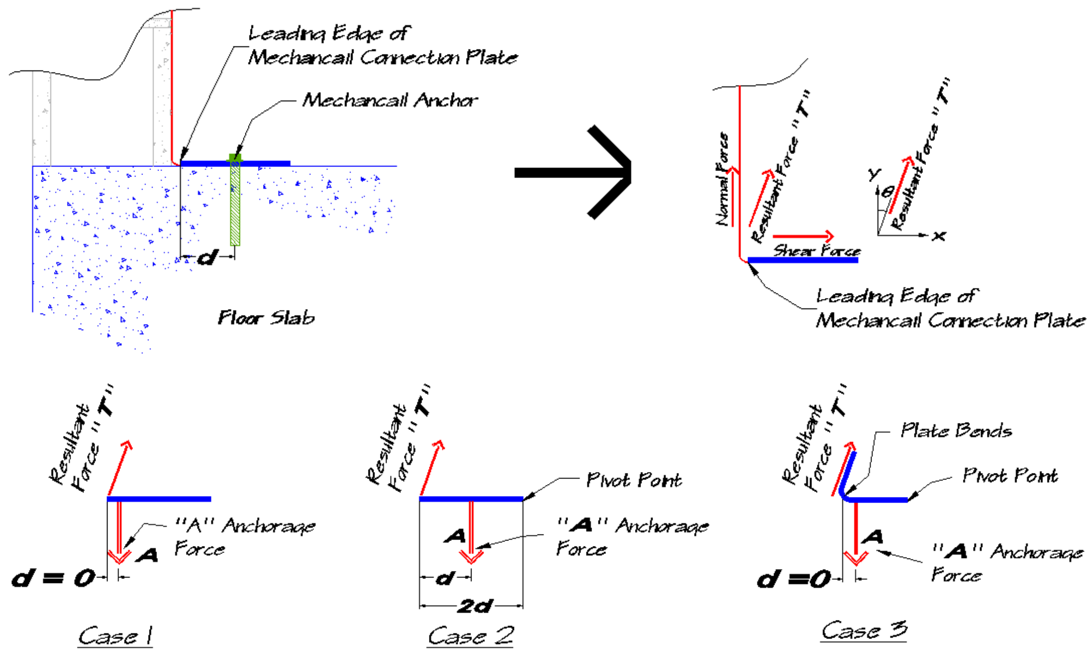


Figure 6 – Schematic of Mechanical Connection Plate and Idealized FBD of the Connection Plate

The first material is a polyvinyl-chloride (PVC) liner. When used in its typical application as an impervious layer under bathroom fixtures, it is generally referred to as a shower pan liner and is readily available at local domestic hardware outlets. The second material is a galvanized sheet steel. Its commercial application is for corrugated metallic roofing and has the trade name Galvalume®. It is important to note that these materials were extensively researched for desirable characteristics for membrane retrofitting. The designer must take steps to insure that fielded system/materials meet or exceed all design assumptions for ductility and durability.

The shower pan liner is applicable to the Case 1 scenario. Due to its low modulus, the membrane force *T* is easily resisted and the anchorage assumption is that the connection plate is rigid to the first line of anchors and that the anchors are placed along the leading edge of the connection plate. These assumptions were validated by results of finite element simulations done using the LS-DYNA computational software as shown in Figure 7. In field experiments, these assumptions were insured by using powder actuated nails, which resulted in an overall efficient installation, completed within 30 minutes (Figure 8A).

The stiffer sheet steel involves the principles in Cases 2 and 3, where *d* is the moment arm, and the connection plate is rigid, thus creating a pivot point. Due to the increased load applied to the connection by the high modulus material, the type of anchorage selected was large diameter concrete screws. These screws require larger drills and a standoff from the wall to be considered. For this example the closest a drill could get to the wall was 3 inches, so Case 2 was employed (Figure 8B), which resulted in an amplification of two to the anchorage ($A = 2T$). When designing connections, it would always be more conservative to design for the Case 2 option due to the amplification of the anchorage force.

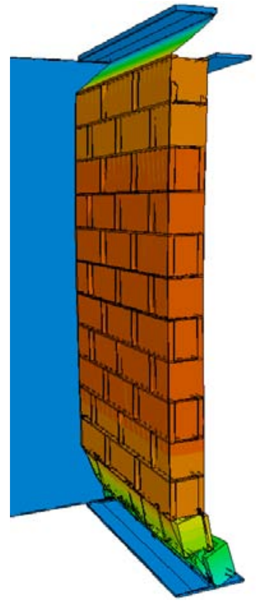


Figure 7 – LS-DYNA Computational Model of Shower Pan Liner Behavior

A B

Figure 8 – Fielded Connections Case 1 and Case 2

BOUNDARY CONDITIONS

To further research the URM wall-retrofit system, a complete understanding of the masonry wall boundary condition was needed. Previous research noted the advantages of the energy absorbing capabilities of the masonry, which must consider the influence of a gap between the wall and supporting structure (Figure 9). When exploring the boundary and infill masonry wall system, it is assumed that the walls act in one-way supported condition and have a rigid supporting frame or structure to resist the planer axially thrust of the masonry wall. In order to normalize the experiments among the numerous experimental laboratories, it is very important to consider the influence of the support structure on its interaction with the masonry wall. Based on the experience of previous AFRL research, the quality and details of

the masonry wall construction can strongly affect the survivability of the tested retrofit.

To assist with this normalization, sample walls were proposed and constructed (Figure 10). These walls represent three idealized conditions where arching can or cannot occur. They also serve as a baseline study that illustrates how the construction of the intended retrofit wall can change the intended experimental results if not properly considered.

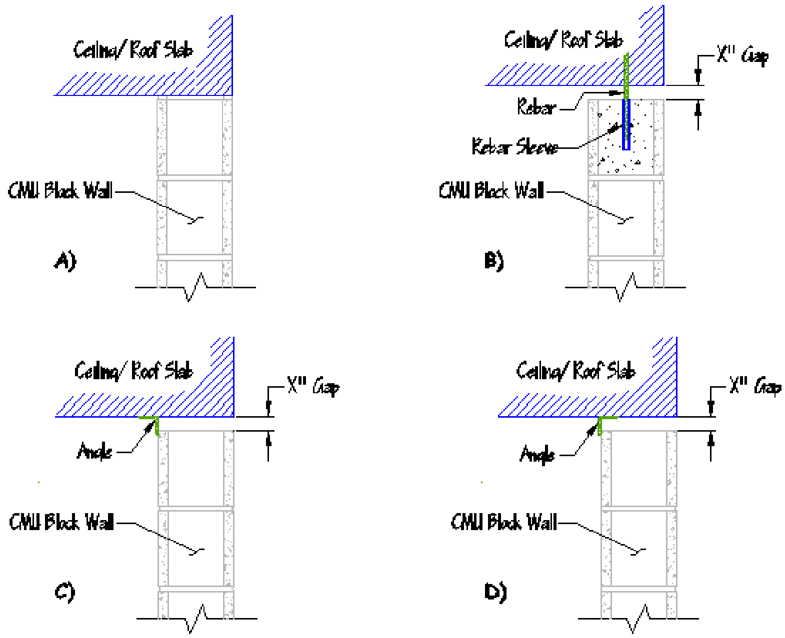


Figure 9 – Idealized Infill Masonry Boundary Conditions

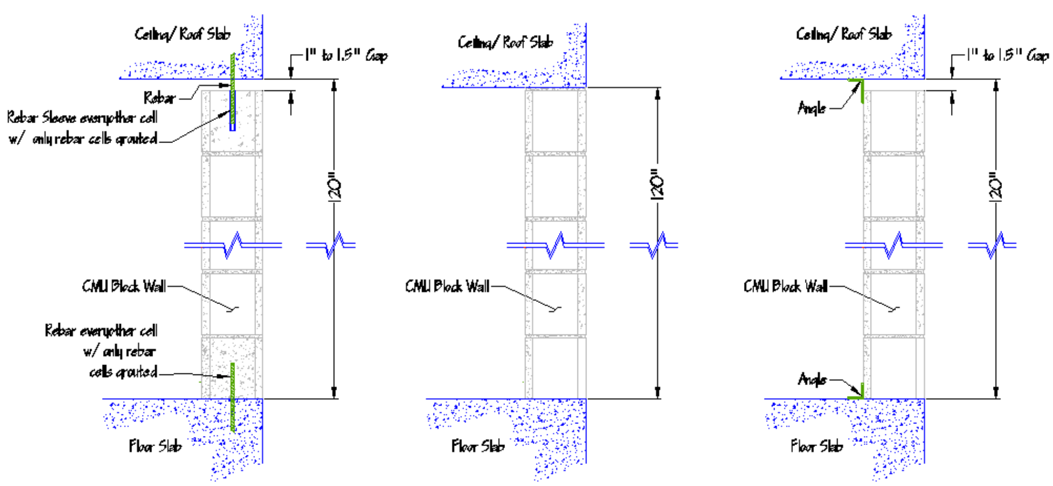


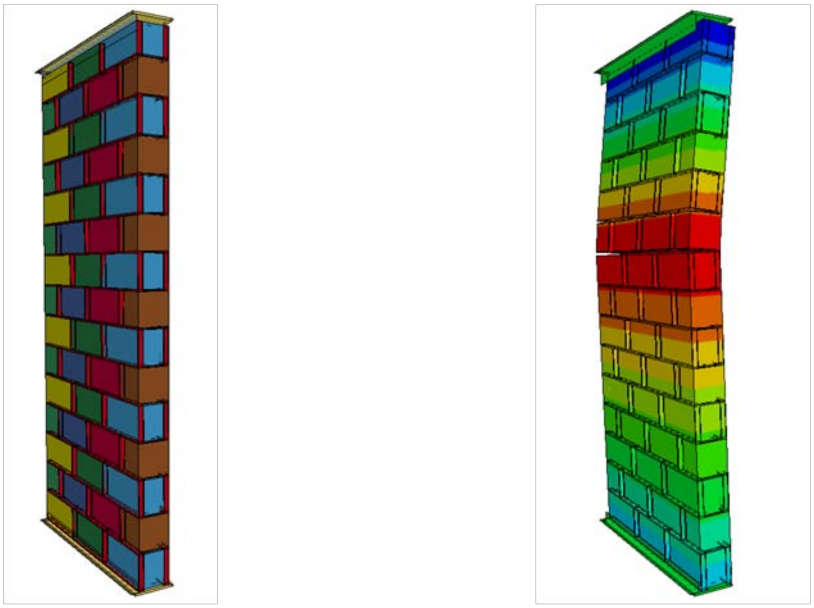
Figure 10 – Experimental Schematic of Proposed Boundary Condition Experiments

To better understand the effects of these boundary conditions, high-fidelity numerical modeling is being conducted to examine the response of the masonry wall alone before a retrofit is included. Computational simulations can provide vital information

that is not able to be collected during live experiments. The modeling of boundary conditions provides insight into the amount of arching provided by a specific design and can help define the load transferred into the retrofit based on the velocity of the failed CMU wall.

Computational modeling of the boundary condition referenced in Figure 9 is detailed here. The numerical simulation used the computational solid dynamics code LS-DYNA (LSTC 2007) to calculate the response. The CMU block and mortar were modeled using the Mat072R3 material model for concrete. The angle was modeled using a linear elastic material model. Concrete screw anchors were modeled by creating rigid nodes at the placement of the anchors. The CMU block and mortar have common nodes and element erosion was imposed to simulate local failures. Single surface contacts were defined for all surfaces.

The results of the calculation (Figure 11) are in good agreement with results of live test data and provide a couple of key insights into this boundary condition. This boundary condition is one that occurs when there is no shear capacity at the ceiling/roof slab. The placement of the angle provides the needed shear capacity to kick the wall into a hinged shape (Figure 11B). Higher fixity condition occurs at the base, and the hinge occurs 1 ½ courses above the centerline of the wall.



A B

Figure 11 – LS-DYNA Simulation of Angle Boundary Condition (A) Model Setup (B) Hinged Shape

Another point of interest is the distribution of stresses on the angle supports. Figure 12 shows the stress distributions at the floor condition and at the ceiling/roof condition. The highest stress concentrations occur at the angle radius and in the vicinity of the anchor connections.

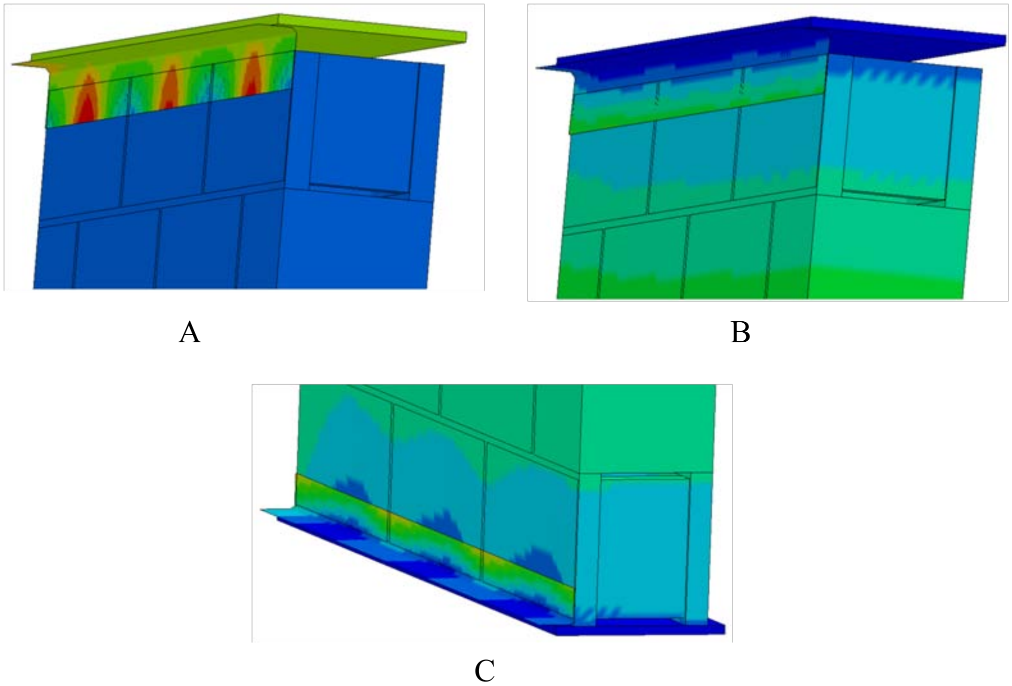


Figure 12 – Connection Behavior; (A) Localized Stresses Near Anchorage; (B) Stress as CMU Wall Rebounds; (C) Typical Base Stress Distribution

The information provided from these simulations provides key data on the behavior of the URM component as a standalone system. These data can be used to modify the approach when designing a retrofit based on the hinged shape of the URM wall and on the energy transmitted from the blast load through the URM wall to the retrofit based on the varying boundary conditions.

CONCLUSIONS AND FUTURE EFFORTS

The intent of this research was to develop procedures for designing membrane-catcher retrofits for infill unreinforced masonry walls. Experimental data have been collected, and efforts are now focused on high-fidelity numerical simulations and analytical model development. The analytical model presented in this paper is simple enough to use with a spreadsheet, and the proposed connection design methodology can be performed by hand with some iteration. Efforts will continue in the development of a design guide for infill-masonry-wall-retrofits. Transition of the analytical results is being considered for future versions of SBEDS (2008) a Single-Degree-of-Freedom Blast Effects Design Spreadsheet, used widely for blast designs of facilities.

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